Economic losses from reduced freshwater under future climate scenarios: An example from the Urumqi River, Tianshan Mountains

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Abstract: As important freshwater resources in alpine basins, glaciers and snow cover tend to decline due to climate warming, thus affecting the amount of water available downstream and even regional economic development. However, impact assessments of the economic losses caused by reductions in freshwater supply are quite limited. This study aims to project changes in glacier meltwater and snowmelt of the Urumqi River in the Tianshan Mountains under future climate change scenarios (RCP2.6 (RCP, Representative Concentration Pathway), RCP4.5, and RCP8.5) by applying a hydrological model and estimate the economic losses from future meltwater reduction for industrial, agricultural, service, and domestic water uses combined with the present value method for the 2030s, 2050s, 2070s, and 2090s. The results indicate that total annual glacier meltwater and snowmelt will decrease by 65.6% and 74.5% under the RCP4.5 and RCP8.5 scenarios by the 2090s relative to the baseline period (1980–2010), respectively. Compared to the RCP2.6 scenario, the projected economic loss values of total water use from reduced glacier meltwater and snowmelt under the RCP8.5 scenario will increase by 435.10×10^6 and 537.20×10^6 CNY in the 2050s and 2090s, respectively, and the cumulative economic loss value for 2099 is approximately 2124.00×10^6 CNY. We also find that the industrial and agricultural sectors would likely face the largest and smallest economic losses, respectively. The economic loss value of snowmelt in different sectorial sectors is greater than that of glacier meltwater. These findings highlight the need for climate mitigation actions, industrial transformation, and rational water allocation to be considered in decision-making in the Tianshan Mountains in the future.

Keywords: glacier meltwater; snowmelt; freshwater supply; water use; economic losses; future climate scenario; climate change; Tianshan Mountains

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1 Introduction

Glacier meltwater and snowmelt constitute a significant source of freshwater resources on Earth and influence water provisioning, hydroelectric power, and extreme weather events (National Research Council, 2012; Brown et al., 2014). More than one-sixth of the human population on

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Earth depends on freshwater supplies contributed by glaciers and seasonal snow cover (Barnett et al., 2005). As global warming accelerates the decline of the cryosphere, the extent of glaciers and snow cover will diminish, and seasonal variation in glacier meltwater and snowmelt runoff is projected to be affected (Barnett et al., 2005; Khadka et al., 2014; IPCC, 2019). This is manifested as an increase in average winter streamflow and an earlier peak in spring streamflow in glacier and snowmelt-dominated alpine basins under future climate scenarios (IPCC, 2019). Consequently, climate change impacts on glacier meltwater and snowmelt runoff will affect freshwater ecosystems, domestic water supplies, and sustainable socioeconomic development (Roberts et al., 2018; Gao et al., 2021).

Climate change affects not only hydrological processes and water resource systems, but also water supply and demand across regions (Arnell, 1999; Duan et al., 2017; Duan et al., 2020). With irrigation, socioeconomic development, and rapid increases in population, water demand is projected to increase significantly (Barnett et al., 2005; Hanasaki et al., 2013; Gain and Wada, 2014; Guo and Shen, 2016). For example, it is evident that the demand of water in South Asian river basins will increase rapidly in the coming decades (Wijngaard et al., 2018). In Xinjiang Uygur Autonomous Region, a semi-arid region of Northwest China, glacier meltwater and snowmelt are critical water resources, and water demand is also be expected to increase in the future (Shen et al., 2020). Simultaneously, freshwater supply and availability will be challenged in the future due to rising temperatures and changes in precipitation.

Serving as the world's water towers, mountain regions provide substantial and relatively constant freshwater resources for lowland river basins (Viviroli et al., 2011; Immerzeel et al., 2020). The Tibetan Plateau contributes 48.0% of the annual discharge of the Indus River Basin, and the glacier meltwater of the Indus River Basin accounts for 40.6% of the total river flow (Immerzeel et al., 2010; Sun et al., 2018). In the upper Heihe River Basin of the Qilian Mountains in China, the average contribution of glacier meltwater and snowmelt to the total streamflow reached 28.9% from 1960 to 2013 (Chen et al., 2018). Similarly, the Tianshan Mountains rely heavily on glacier meltwater and snowmelt due to their long distance from the oceans. Zhang et al. (2016a) found that the contribution of glacial meltwater to runoff in several catchments of the Tianshan Mountains ranged from 3.5% to 67.5%, with an average of 24.0% during 1961–2007. Nevertheless, the snow cover area of the Tianshan Mountains has decreased significantly and glacier shrinkage has accelerated under a warming climate (Sorg et al., 2012; Farinotti et al., 2015; Chen et al., 2019). As a consequence, these variations will alter the quantity of runoff and water storage capacity, thereby affecting downstream water supply in glacier and snowmelt-dependent watersheds (Chen et al., 2016).

The remarkable reduction of freshwater supply under climate change will not only affect the cryosphere process and ecological environment, but also cause major economic losses. In the Arctic region, the economic cost due to reductions in snow cover with global warming is estimated at 34.0×10^9–650.0×10^9 USD for 2010–2100 (Euskirchen et al., 2013). In the western USA, the shift from snowfall to rainfall conditions will cause annual economic losses of 10.8×10^9– 48.6×10^9 USD (Sturm et al., 2017). Moreover, the value of snow mass loss in western China will increase in the future (Wu et al., 2020). In particular, Xinjiang plays an irreplaceable strategic role in the construction of the "Silk Road Economic Belt" and constitutes the core area of the new Silk Road (Han and Li, 2018). Decreasing water resources are bound to challenge the construction of the core area of this economic belt. Additionally, the supply of freshwater provides a range of direct and indirect services that are necessary for human livelihoods, including domestic use and power generation (Aylward et al., 2005). As a result, cryosphere service valuation has received widespread public attention in recent years, such as the evaluation of glacier, snow, and permafrost service values (Xiao et al., 2015; Chen et al., 2019; Yang et al., 2019; Sun et al., 2020; Wu et al., 2020; Ying, 2020).

Considering the monetary valuation of freshwater resources, it is necessary for the public and policy-makers to understand the economic significance of changes in water supply. We consider the Urumqi River as an example, which is situated on the northern slope of the Tianshan

Mountains and is mainly recharged by precipitation, glacier meltwater and snowmelt. Most previous studies on the Urumqi River have focused on cryosphere processes and changes as well as the impacts of climate change (Li et al., 2010; Kong and Pang, 2014; Sun et al., 2015; Han et al., 2016; Zhang et al., 2016b). Economic impact and quantitative analyses of glacier meltwater and snowmelt reduction on this region have been less of a focus. Thus, this study (1) analyzes the relative contribution and characteristics of glacier meltwater and snowmelt to outlet streamflow in the Urumqi River in the 2030s, 2050s, 2070s, and 2090s using five global climate models and three representative concentration pathway (RCP) scenarios, and (2) reveals the associated economic losses from these meltwater reductions for industrial, agricultural, service, and domestic water uses based on the present value assessment approach.

2 Study area and methodology

2.1 Study area

The Urumqi River (43°00′–44°07′N, 86°45′–87°56′E), with elevations ranging from 1892 to 4461 m (Fig. 1), is located on the northern slope of the Tianshan Mountains in Xinjiang Uygur Autonomous Region of Northwest China. The basin originates from Urumqi Glacier No. 1 on the northern side of the Tianger Peak No. II and flows to the northeast. Influenced by westerly circulation, it is characterized by a temperate continental arid climate. The Urumqi River with a total length of 214 km and a total area of 4684 km^2 flows through the center of Urumqi City, which is the political, economic, and cultural center of Xinjiang (Kong and Pang, 2014; Zhang et al., 2019). The Urumqi River provides the necessary water resources for the city of Urumqi. As Xinjiang's largest economy, Urumqi City is located in the economic belt on the northern slope of the Tianshan Mountains. This economic belt supports 56.0% of Xinjiang's total GDP, but its water resources account for only approximately 7.4% of the total (Zhang, 2018). The drainage area of the Urumqi River Basin located above the outlet of the Yingxiongqiao Hydrographic Station is 924 km^2 with an average elevation of 3066 m. There are 124 glaciers above the outlet, and the total statistical glacial area is 38 km^2 (4.1% of the watershed area). The annual average precipitation and streamflow in the basin were recorded as 526 mm and 2.42×10^8 m^3, respectively (Sun et al., 2015).

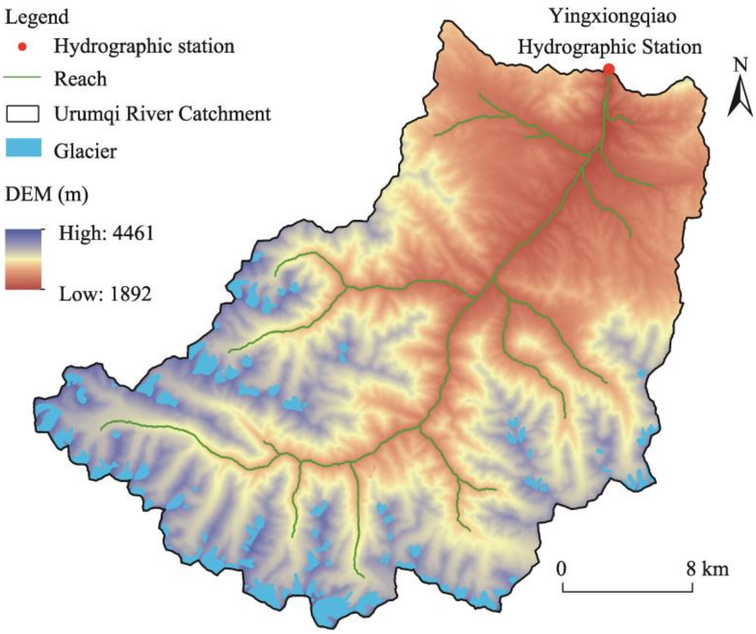

Fig. 1 Overview of the Urumqi River catchment

2.2 Data sources

In this study, future climate data projections were obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) global climate models (1950–2099) (Taylor et al., 2012). Given the impact of uncertainties in hydrological simulations from a single climate model, we used five global climate model datasets (namely, GFDL–ESM2M, IPSL–CM5A–LR, MIROC–ESM–CHEM, NorESM1–M, and HadGEM2–ES) that are applicable to China after downscaling and bias correction (Su et al., 2016; Venkataraman et al., 2016). Projections of future climate data and hydrological impacts were also based on assumptions of different greenhouse gas emission scenarios. Therefore, RCP2.6, RCP4.5, and RCP8.5 scenarios were chosen to represent future climate change scenarios, which characterize low, moderate, and high greenhouse gas emissions, respectively. Furthermore, the RCP8.5 scenario was expected to result in the most warming by the end of 2100. For comparisons to the baseline period (1980–2010), the future time was divided into four periods, namely, the 2030s (2020–2039), 2050s (2040–2059), 2070s (2060–2079), and 2090s (2080–2099). In addition, the water amounts of the industrial, agricultural, service, and domestic sectors of Urumqi City in 2016 were derived from the Xinjiang Statistical Yearbook (Bureau of Statistics of Xinjiang Uygur Autonomous Region, 2017) and Xinjiang Water Resources Bulletin (Water Resources Department of Xinjiang Uygur Autonomous Region, 2016). The corresponding water prices for the industrial, service, and domestic sectors in 2016 were collected from the website http://www.chinaxinjiang.cn/, and the water price of agricultural irrigation was obtained from local farmers in Urumqi County.

2.3 Methodology

In this study, a distributed cryospheric basin hydrological model was employed to simulate the contribution of glacier meltwater and snowmelt to streamflow in the Urumqi River under future climate change scenarios. Detailed descriptions and accuracy evaluations of this model can be found in Chen et al. (2018) and Zhang et al. (2021). A snow valuation model proposed by Sturm et al. (2017) was used to assess future economic losses of sectorial water uses due to declining glacier melt and snowmelt. This method refers to the concept of the present value or using today's water amounts or currency to quantify the value of future losses. The present value is discounted by the discount factor D_i (a financial concept according to which future value decreases over time). The present value of meltwater losses in the reference year i is expressed as follows:

$$V_i=P_i\times W_i\times D_i, \tag{1}$$

where V_i (CNY) is the present value of meltwater losses in the reference year i; P_i (CNY/m^3) represents the water price in the year i; W_i (m^3) is the amount of water that will be lost in a future year relative to the year i; and D_i (%) is the discount factor associated with the discount rate of r (where r represents the rate at which the future value declines relative to the present day level) and it can be calculated as: $D_i=1/(1+r)^i$ (where i is measured from the present (i=0) and thus incremented to future years). Discount rates of 1%, 3%, and 6% are usually used in climate studies (Sturm et al., 2017). Li (2018) indicated that a lower discount rate will lead to a relatively high social cost of carbon, which tends to reduce emissions significantly. Therefore, under a low greenhouse gas emission scenario, the resulting economic loss is less pronounced, and the corresponding discount rate is higher. From this, the discount rates given by the RCP2.6, RCP4.5, and RCP8.5 scenarios are 6%, 3%, and 1%, respectively.

To calculate the value of meltwater losses in different sectors, we assume that the proportion of water used in each sector is constant over time, so the change of the above equation is as follows:

$$V_i=P_i\times W_i\times D_i\times S_{ij}, \tag{2}$$

where S_{ij} (%) is the percentage of the j^{th} sectorial water use of the total water amount in the reference year i. In this paper, the reference year i is 2016, and the calculated P and S values are the constants. Since we divided future years into four time periods (2030s, 2050s, 2070s, and

2090s), the cumulative meltwater loss value (V_{cum}) for different time periods is calculated as follows:

$$V_{\mathrm{cum}} = PS\sum_{i=1}^{n} W_i D_i \ . \tag{3}$$

Hydrological simulation and projection were carried out with MATLAB software, and the present value assessment of meltwater losses was based on the descriptive statistical analyses.

3 Results

3.1 Projections of glacier meltwater and snowmelt changes

The projected changes in the annual glacier meltwater and snowmelt of the Urumqi River are presented in Figure 2. Both glacier meltwater and snowmelt will exhibit a decreasing trend in the future period under different RCP scenarios. Snowmelt decreases faster under the RCP8.5 scenario than under the RCP2.6 and RCP4.5 scenarios. The mean amount of snowmelt is projected to be 0.60×10^8, 0.52×10^8, and 0.43×10^8 m^3 from 2017 to 2099 under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. However, the projection of glacier meltwater shows no clear differences under the three RCP scenarios. By the end of the 21st century, glacier meltwater will be reduced to less than 0.21×10^8 m^3. The contribution of glacier meltwater to outlet streamflow shows a slight decreasing trend during the projected period under the three RCP scenarios, but the three climate scenarios do not significantly differ (Fig. 3). The projection of the snowmelt contribution rate also decreases under different RCP scenarios. Additionally, under the RCP8.5 scenario, the contribution rate of snowmelt decreases faster than that under the RCP2.6 and RCP4.5 scenarios, with average values of 22.9%, 20.4%, and 16.5% under the RCP2.6, RCP4.5, and RCP8.5 scenarios for 2017–2099, respectively.

Table 1 shows the changes in glacier meltwater and snowmelt in the four time periods of the 21st century relative with the baseline period (1980–2010) under the RCP2.6, RCP4.5, and

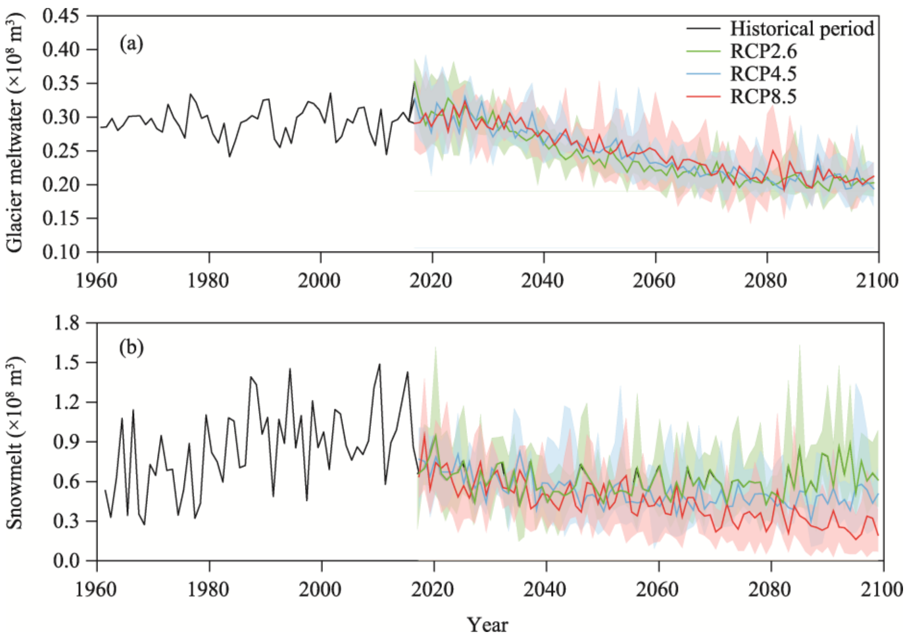

Fig. 2 Changes of annual glacier meltwater (a) and snowmelt (b) of the Urumqi River for the historical period (1961–2016) and projected period (2017–2099) under the three Representative Concentration Pathway (RCP) scenarios (RCP2.6, RCP4.5, and RCP8.5). Shaded area represents the annual variation range projected by the five Coupled Model Intercomparison Project Phase 5 (CMIP5) models. The average value of model ensemble for each RCP scenario is indicated by a thick line.

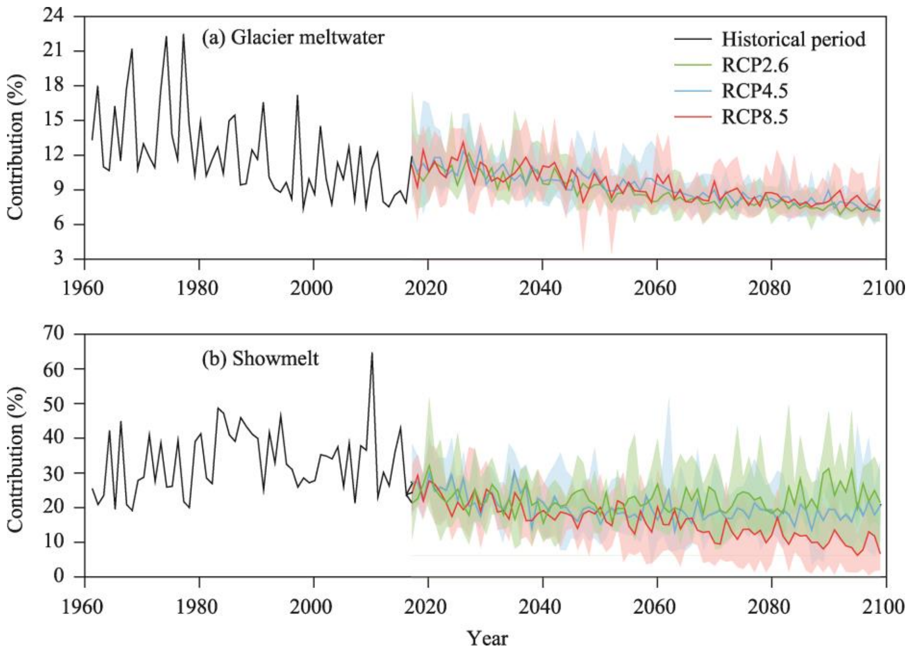

Fig. 3 Contributions of glacier meltwater (a) and snowmelt (b) to streamflow of the Urumqi River for the historical period (1961–2016) and projected period (2017–2099) under the three RCP scenarios (RCP2.6, RCP4.5, and RCP8.5). Shaded area represents the annual variation range projected by the five CMIP5 models. The average value of model ensemble for each RCP scenario is indicated by a thick line.

Table 1 Changes of glacier meltwater and snowmelt of the Urumqi River in the 2030s, 2050s, 2070s, and 2090s relative to the baseline period (1980–2010) under the three Representative Concentration Pathway (RCP) scenarios

Meltwater	Scenario	2030s	2050s	2070s	2090s
Glacier meltwater ($\times10^8$ m^3)	RCP2.6	–5.74	–4.64	–4.15	–3.95
	RCP4.5	–5.72	–4.96	–4.27	–3.99
	RCP8.5	–5.73	–5.04	–4.35	–4.14
Snowmelt ($\times10^8$ m^3)	RCP2.6	–12.66	–10.99	–11.46	–12.88
	RCP4.5	–12.66	–10.06	–9.30	–9.28
	RCP8.5	–11.65	–9.43	–7.12	–5.70

RCP8.5 scenarios. Total annual glacier meltwater respectively decreases by 34.8%, 47.2%, 52.8%, and 55.1% for the 2030s, 2050s, 2070s, and 2090s under the RCP2.6 scenario. The projected decreases in the corresponding four time periods reach up to 35.0%, 43.6%, 51.4%, and 54.6% under the RCP4.5 scenario, respectively, and 34.8%, 42.7%, 50.5%, and 52.9%, respectively, under the RCP8.5 scenario. Notably, glacier meltwater decreases much faster in the 2070s and 2090s than in the 2030s and 2050s, and the decrease in meltwater under the RCP2.6 scenario is slightly greater than those under the RCP4.5 and RCP8.5 scenarios. Similar to that found for glacier meltwater, the projected changes in total annual snowmelt relative to the baseline period are expected to decrease in the four time periods. Under the RCP2.6 scenario, the projected snowmelt decreases by 57.4%, 63.1%, 61.5%, and 56.7% in the 2030s, 2050s, 2070s, and 2090s, respectively. Snowmelt decreases faster under the RCP4.5 and RCP8.5 scenarios than under the RCP2.6 scenario. In particular, the projected snowmelt in the 2030s, 2050s, 2070s, and 2090s respectively decreases by 57.4%, 66.2%, 68.7%, and 68.8% under the RCP4.5 scenario and by 60.8%, 68.3%, 76.1%, and 80.8% under the RCP8.5 scenario. Meanwhile, the estimated snowmelt in the 2070s and 2090s shows a much greater decrease than that in the 2030s and 2050s. Total amount of glacier meltwater and snowmelt in the 2030s, 2050s, 2070s, and 2090s decreases

by 52.3%, 61.0%, 64.8%, and 65.6% under the RCP4.5 scenario, respectively, and by 54.9%, 62.5%, 70.2%, and 74.5% under the RCP8.5 scenario, respectively. Under the RCP2.6 scenario, the reduction in total meltwater undergoes a small change in different time periods. In general, the glacier meltwater and snowmelt projected by the three RCP scenarios are reduced compared to the baseline period, with the decreasing rate being more rapid in the far future (after the 2050s).

3.2 Projected economic loss values

3.2.1 Economic losses of meltwater for various sectorial water uses

We calculated the economic loss and gain values of glacier meltwater for the 2030s, 2050s, 2070s, and 2090s under the RCP2.6, RCP4.5, and RCP8.5 scenarios based on the present value in 2016 (Table 2). By the 2030s, there are economic gain values of glacier meltwater for various sectorial water uses under different RCP scenarios, which vary from 0.01×10^6 CNY for agricultural water use to 1.70×10^6 CNY for industrial water use. However, the estimated economic loss values are found to range between 0.50×10^6 CNY (RCP2.6 scenario) and 20.00×10^6 CNY (RCP8.5 scenario) by the 2050s. Under the RCP2.6 and RCP8.5 scenarios, the economic loss values increase by 0.20×10^6–32.70×10^6 CNY by the 2070s, and vary from 0.10×10^6 to 28.10×10^6 CNY by the 2090s. In general, the economic loss value by the 2070s is greater than those by the 2050s and 2090s except under the RCP2.6 scenario. The economic loss value of industrial water use is the greatest with a total loss value of 80.60×10^6 CNY (RCP8.5 scenario) occurring by the end of the 21st century, while the economic loss value of agricultural water use is the lowest, at 6.47×10^6 CNY.

Table 2 Estimated economic loss and gain values of glacier meltwater for various sectorial water uses under the three RCP scenarios

Scenario	Sectorial water use	Economic loss/gain value ($\times10^6$ CNY)			
		2030s	2050s	2070s	2090s
RCP2.6 (*r*=6%)	Industrial water use	+1.70	–6.20	–2.90	–1.10
	Agriculture water use	+0.10	–0.50	–0.20	–0.10
	Service water use	+0.80	–2.70	–1.30	–0.50
	Domestic water use	+1.10	–4.10	–1.90	–0.70
RCP4.5 (*r*=3%)	Industrial water use	+0.05	–11.40	–12.60	–8.20
	Agriculture water use	+0.01	–0.90	–1.00	–0.70
	Service water use	+0.02	–5.00	–5.50	–3.60
	Domestic water use	+0.03	–7.40	–8.30	–5.40
RCP8.5 (*r*=1%)	Industrial water use	+0.20	–20.00	–32.70	–28.10
	Agriculture water use	+0.01	–1.60	–2.60	–2.30
	Service water use	+0.10	–8.80	–14.30	–12.30
	Domestic water use	+0.10	–13.10	–21.40	–18.40

Note: *r*, discount rate; +, economic gain; –, economic loss.

Table 3 shows the economic loss values of snowmelt for various sectorial water uses for the four time periods under the corresponding RCP scenarios. It is clear that the economic loss values of snowmelt for various sectorial water uses are greater than those of glacier meltwater because the future annual amount of snowmelt decline is much greater than that of glacier meltwater compared to 2016. Specifically, the economic loss values of snowmelt for sectorial water uses are estimated at 6.50×10^6–193.20×10^6 CNY by the 2030s and at 3.10×10^6–224.50×10^6 CNY by the 2050s. By the 2070s and 2090s, the estimated economic loss values range from 0.90×10^6 CNY (RCP2.6 scenario) to 237.70×10^6 CNY (RCP8.5 scenario) and from 0.20×10^6 CNY (RCP2.6 scenario) to 222.80×10^6 CNY (RCP8.5 scenario), respectively. Especially under the RCP8.5 scenario, the economic loss values of all sectorial water uses by the 2070s are greater than the values for the other time periods. In addition, the greatest economic loss occurs in the industrial sector, reaching 878.20×10^6 CNY (RCP8.5 scenario) over the period of 2020s–2090s.

Table 3 Estimated economic loss value of snowmelt for various sectorial water uses under the three RCPs scenarios

Scenario	Sectorial water use	Economic loss value ($\times 10^6$ CNY)			
		2030s	2050s	2070s	2090s
RCP2.6 (r=6%)	Industrial water use	–81.30	–38.20	–10.70	–2.70
	Agriculture water use	–6.50	–3.10	–0.90	–0.20
	Service water use	–35.60	–16.80	–4.70	–1.20
	Domestic water use	–53.30	–25.10	–7.00	–1.80
RCP4.5 (r=3%)	Industrial water use	–120.30	–106.70	–66.70	–37.30
	Agriculture water use	–9.70	–8.60	–5.40	–3.00
	Service water use	–52.80	–46.80	–29.30	–16.30
	Domestic water use	–78.90	–70.00	–43.80	–24.40
RCP8.5 (r=1%)	Industrial water use	–193.20	–224.50	–237.70	–222.80
	Agriculture water use	–15.50	–18.00	–19.10	–17.90
	Service water use	–84.70	–98.50	–104.20	–97.70
	Domestic water use	–126.70	–147.30	–155.90	–146.10

For the economic loss values of total glacier meltwater and snowmelt, the economic values of sectorial water uses decrease by 6.40×10^6 CNY (RCP2.6 scenario) to 193.00×10^6 CNY (RCP8.5 scenario) and by 3.60×10^6 CNY (RCP2.6 scenario) to 244.60×10^6 CNY (RCP8.5 scenario) for the 2030s and 2050s, respectively (Tables 2 and 3). By the 2070s and 2090s, the projected economic loss values of total glacier meltwater and snowmelt vary from 1.10×10^6 CNY (RCP2.6 scenario) to 270.40×10^6 CNY (RCP8.5 scenario) and from 0.30×10^6 CNY (RCP2.6 scenario) to 250.80×10^6 CNY (RCP8.5 scenario), respectively. Moreover, the economic loss value of total glacier meltwater and snowmelt for each sector shows different results under the three RCP scenarios in the future (Fig. 4). For the RCP2.6 scenario, the difference in the average economic loss value of the four sectorial water uses in the future period is relatively small. Under the RCP8.5 scenario, the economic losses from the reduction of glacier meltwater and snowmelt are greater than those under the RCP2.6 and RCP4.5 scenarios, in which the economic losses of industrial, agricultural, service, and domestic water uses are 11.80×10^6, 0.90×10^6, 5.20×10^6, and 7.70×10^6 CNY on average, respectively.

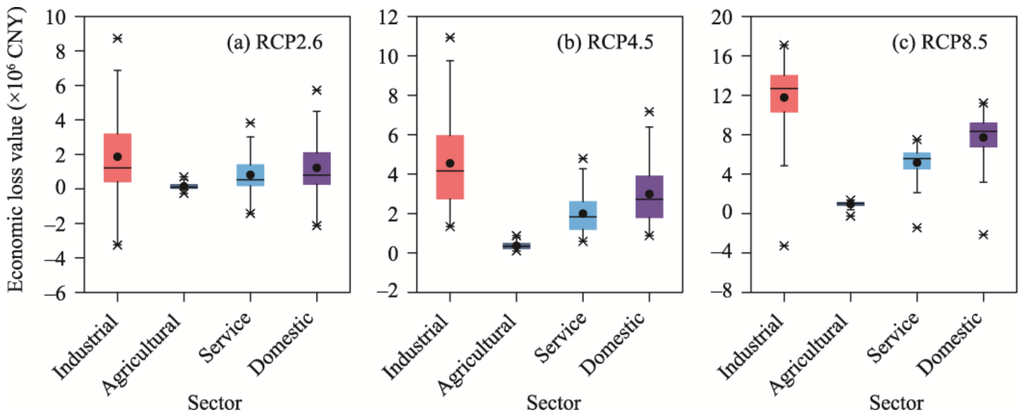

Fig. 4 Box plots of the estimated economic loss values of total glacier meltwater and snowmelt for different sectorial water uses under the three RCP scenarios. (a), RCP2.6; (b), RCP4.5; (c), RCP8.5. The boxes represent the range from the lower quantile (Q25) to the upper quantile (Q75). The black dots and black horizontal lines represent the means and medians, respectively. The upper and lower whiskers indicate the maximum and minimum values, respectively.

3.2.2 Economic losses of meltwater for total water use

In addition to the estimates of the economic loss values of sectorial water uses, we also evaluated the economic loss value of glacier meltwater and snowmelt for total water use under different RCP scenarios (Fig. 5). Economic losses from glacier meltwater and snowmelt reduction under the RCP2.6 and RCP4.5 scenarios are expected to decrease in the four future time periods. Especially under the RCP2.6 scenario, the economic loss value is reduced to less than 10.00×10^6 CNY. Under the RCP8.5 scenario, the economic loss value shows an increase in volatility and ranges from 419.70×10^6 CNY by the 2030s to 545.40×10^6 CNY by the 2090s. The cumulative economic loss value of total reduction of glacier meltwater and snowmelt is shown in Figure 6. Before 2030, there is a slight increase in the cumulative economic loss, with values of 133.60×10^6, 174.10×10^6, and 249.40×10^6 CNY under the RCP2.6, RCP4.5, and RCP8.5 scenarios, respectively. By the middle of the 21st century, the estimated cumulative economic loss values rise to 267.40×10^6, 446.50×10^6, and 750.40×10^6 CNY under the three RCP scenarios, respectively. By the end of the 21st century, the cumulative economic loss value under the RCP8.5 scenario increases faster than those under the RCP2.6 and RCP4.5 scenarios, with an estimate of 2124.00×10^6 CNY in total.

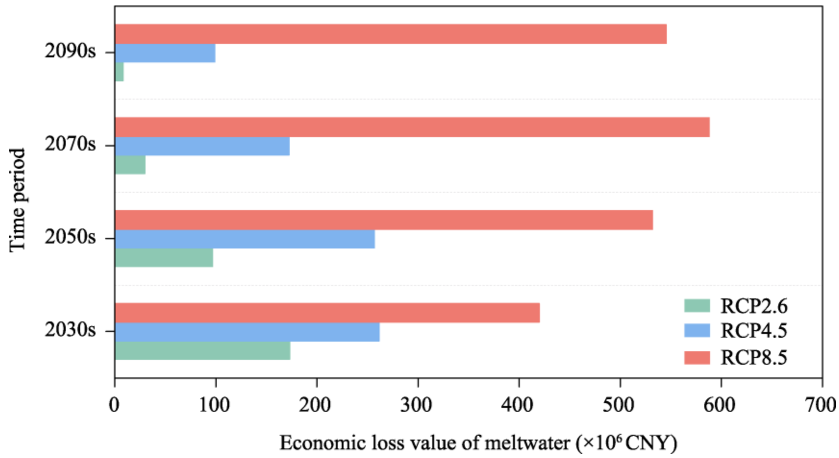

Fig. 5 Estimated economic loss values of glacier meltwater and snowmelt for total water use under the three RCP scenarios for the 2030s, 2050s, 2070s, and 2090s

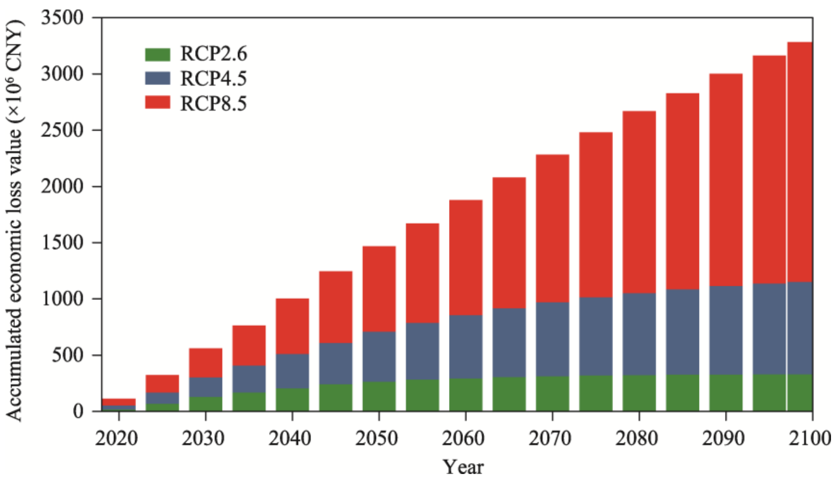

Fig. 6 Projected cumulative economic loss values of glacier meltwater and snowmelt for total water use under the three RCP scenarios from 2020 to 2099

4 Discussion

4.1 Implications of climate change for glacier melt and snowmelt

It is well known that climate change will significantly affect regional river flow regimes, especially for high-altitude mountain regions where meltwater dominated by glaciers and snow cover is the key component of total basin runoff (Arnell and Gosling, 2013; Lutz et al., 2014). Future changes in relevant climate variables (temperature and precipitation) will directly influence runoff projection under different greenhouse gas emission scenarios. A previous study by Su et al. (2017) found that the underestimation of temperature and precipitation could create more uncertainty in discharge projections of the upper Yangtze River, China. Our finding of a projected decreasing trend in annual glacier meltwater in the Urumqi River is consistent with the result of Zhang et al. (2016b), who found that glacier melt will decrease faster under the RCP8.5 scenario than under the RCP2.6 and RCP4.5 scenarios. Moreover, our results show no clear differences among the three RCP scenarios, and a similar change was found in the projected contribution rate of the glacier meltwater to total runoff. The above results may be attributed to the uncertainties in climate projections that lead to differences in glacier meltwater estimates, especially in terms of the impacts of precipitation changes (Huss et al., 2008; Zhang et al., 2012). As emphasized by Soleimani et al. (2017), precipitation projections are generally less robust than temperature projections because precipitation involves more complex local processes. In the present study, both annual temperature and precipitation under future climate scenarios are projected to increase (Fig. 7). Although glacier retreat is faster under the RCP8.5 scenario than under the RCP2.6 and RCP4.5 scenarios due to a faster increase in temperature, glacier retreat is decelerated by a general increase in precipitation under the high greenhouse gas emission scenario. This pattern ultimately leads to insignificant differences in glacier runoff across the scenarios. In addition to climate models, the uncertainty of runoff projection is also related to hydrological models and downscaling approaches. A previous study indicated that hydrological models and Global Climate Models (GCMs) contribute to uncertainty in streamflow projections of the upper Yellow River Basin in China (Vetter et al., 2014). Similarly, for the upper Yangtze

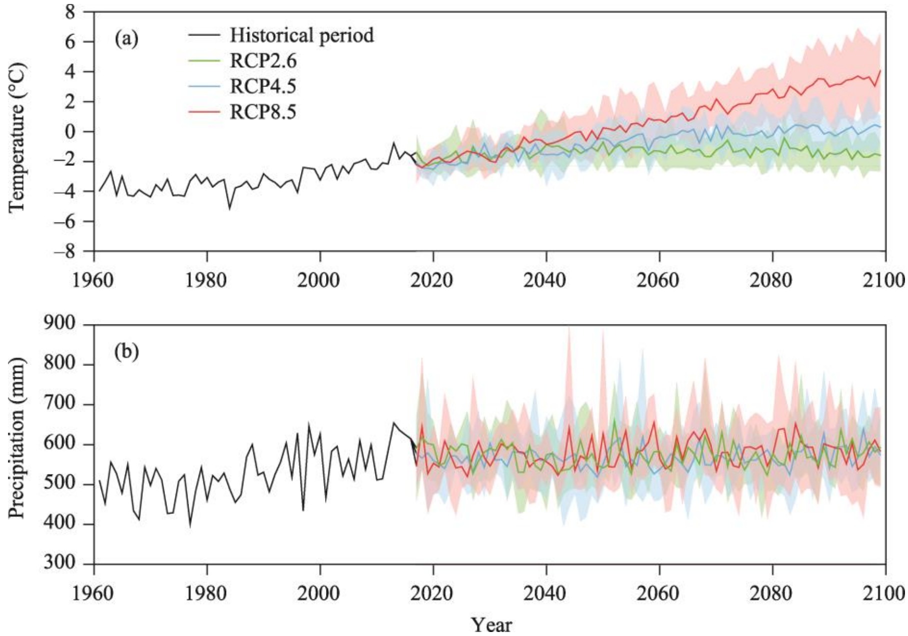

Fig. 7 Changes in temperature (a) and precipitation (b) in the Urumqi River during the historical period (1961–2016) and projected period (2017–2099) under the three RCP scenarios. Shaded area represents the annual variation range projected by the five CMIP5 models. The average value of model ensemble for each RCP scenario is indicated by a thick line.

River in China, the uncertainty of discharge projection is mainly due to GCMs, followed by the effects of hydrological models (Su et al., 2017). A recent study on the projection of glacier runoff in Urumqi Glacier No. 1 in the Tianshan Mountains found that different climate change scenarios can cause great uncertainty in projections (Gao et al., 2018). Therefore, integrative uncertainty assessments must be conducted in future simulations.

For the estimation of future snowmelt of the Urumqi River, the uncertainty of future snowmelt prediction is relatively small due to minor uncertainties of future temperature variation. The estimated mean annual temperature under the RCP2.6 scenario increases by 1.48 ℃, 1.91 ℃, 1.79 ℃, and 1.68 ℃ in the 2030s, 2050s, 2070s, and 2090s relative to the baseline period, respectively. The greatest increase is expected to occur by the middle of the 21st century. Under the RCP4.5 and RCP8.5 scenarios, the projected temperature increases faster than that under the RCP2.6 scenario. There is no doubt that the future increase in temperature will lead to earlier snowmelt and a reduction in winter snow accumulation, resulting in less runoff during the snowmelt season (Clow, 2010; Jain et al., 2010; Shen et al., 2018). In addition, an increase in temperature during a certain period in the future causes a shift to liquid precipitation, so predictions of future snowmelt show a decreasing trend under these three RCP scenarios. Wang et al. (2010) and Lutz et al. (2014) also found that an increase in air temperature is accompanied by a decrease of snowmelt runoff in different glacier and snowmelt-affected areas in the future.

4.2 Implications of the evaluation

In recent decades, population growth, economic development, and the impacts of climate change have led to an intensifying conflict between water supply and demand (Wang et al., 2016; Arsiso et al., 2017; Duan et al., 2019). The resulting water shortage has affected industrial and agricultural production and domestic water use, threatening the environment and ecosystems (Guo and Shen, 2016; Shen et al., 2020). Research has shown that in Northwest China, future agricultural irrigation water demand will exhibit an increasing trend and the increase in runoff will not meet the irrigation water demand (Guo and Shen, 2016). With scarce annual precipitation in Xinjiang, water shortage has become a major factor in limiting the social and economic development in this region (Shen et al., 2013). However, total annual water consumption and per capita water consumption in Xinjiang have generally increased since 2000, while water consumption of 1.00×10^4 CNY GDP has shown a decreasing trend (Zhang, 2018). There are significant regional differences in Xinjiang, and each area has formed characteristic industrial structure systems over different periods of time. As Urumqi City is located in the economic belt on the northern slope of the Tianshan Mountains, its secondary and tertiary industries have developed rapidly, such as through the prioritized development of high-tech development zones and industrial parks (Zhang, 2016). Although water use per 1.00×10^4 CNY GDP of Urumqi City is the lowest in northern Xinjiang, the local irrigation water utilization coefficient and repetition rate of industrial water use are not high, and agricultural water use accounts for more than 60.0% of total water use (Li, 2012).

Based on the existing industrial structure of Urumqi City in 2016, our predicted economic loss values of glacier meltwater and snowmelt are higher for the industrial and service sectors and lower for the agricultural sector. Correspondingly, the water-input-output table of 2030 constructed by Wang (2019) showed that the water uses of industrial and service sectors will be higher than the water use of agricultural sector, and agricultural water consumption will tend to decrease in the future. Considering the impact of the current sectorial water use structure on the economy, the development of high-efficiency water-saving irrigation and the promotion of agricultural transformation are needed to achieve agricultural modernization (Kang, 2019; Biswas et al., 2020; Shaikh et al., 2021). In recent years, Urumqi City has launched a series of water conservation campaigns. The improvement of citizens' awareness of water conservation and the adjustment of water prices will result in a more reasonable use of water resources. In addition, for the sustainable development of the economy and environment, Urumqi City should prioritize the development of high-tech and tertiary industries in the future (Zhang, 2016). The city has already

established the largest wind power plant in Asia. As a result, the rapid development of new and clean energy is more conducive to promoting the transformation of the industry.

According to our results, the economic loss values of glacier meltwater and snowmelt under the RCP8.5 scenario increase by 435.10×10^6 and 537.20×10^6 CNY in the 2050s and 2090s, respectively, compared to the RCP2.6 scenario. It is undeniable that the economic loss value of glacier meltwater and snowmelt is even more pronounced and significant under the high greenhouse gas emission scenario. In contrast, the economic loss value of glacier meltwater and snowmelt tends to decrease under lower greenhouse gas emission scenarios in the future time period. This may be partly due to the different discount rates chosen for the different scenarios (the discount factor decreases over time), with lower greenhouse gas emission scenarios corresponding to the higher discount rates. This leads to a faster decline in economic value under the low greenhouse gas emission scenario in the future. On the other hand, the economic loss value of glacier meltwater and snowmelt is much greater under the high greenhouse gas emission scenario. As a result, the economic loss value tends to decrease under the RCP2.6 and RCP4.5 scenarios and increase under the RCP8.5 scenario in the future. In addition, since our present value approach uses 2016 as the reference year, we are concerned with the economic loss value relative to the reference year and not with the direct market value generated by meltwater provisioning. The results also emphasize that taking active and effective measures to reduce carbon emissions and experiencing the least warming in the middle of the 21st century will facilitate the reduction of even more economic losses. Wu et al. (2020) also showed that curbing carbon emissions can reduce the economic value of snow cover loss.

5 Conclusions

Quantifying the economic significance of declining freshwater supplies is of great importance to water resources management and decision-making. In this study, we quantitatively assessed the economic losses from future meltwater reduction for sectorial water uses based on simulations of glacier meltwater and snowmelt in the Urumqi River, Tianshan Mountains. The results show that compared to the baseline period, total amount of glacier meltwater and snowmelt in the 2030s, 2050s, 2070s, and 2090s decrease by 52.3%, 61.0%, 64.8%, and 65.6%, respectively, under the RCP4.5 scenario and by 54.9%, 62.5%, 70.2%, and 74.5% under the RCP8.5 scenario, respectively. Correspondingly, the economic loss values of various sectorial water uses are projected to decrease under the RCP2.6 and RCP4.5 scenarios from the 2030s to 2090s. For the RCP8.5 scenario, the economic loss value increases from 419.70×10^6 CNY in the 2030s to 545.4×10^6 CNY in the 2090s, with the cumulative economic loss value of 2124.00×10^6 CNY by the end of the 21st century. It was also found that the economic loss value of snowmelt for various sectorial water uses is greater than that of glacier meltwater over the four future time periods. The economic loss value is expected to be the highest for the industrial sector and the lowest for the agricultural sector. Based on the above results, it is suggested that climate mitigation and adaptation actions, such as curbing CO_2 emissions and promoting clean energy, should be actively implemented to reduce the economic value of future meltwater losses. It should also be noted that there is a need to adopt local differential water pricing to improve the efficiency of water resource utilization. Based on this research, future work will be devoted to assessing the economic loss of cryosphere meltwater in other basins in the economic belt of the northern slope of the Tianshan Mountains by combining future climate scenarios and socioeconomic pathways. Such work may enable more reasonable water availability and sustainable development.

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